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A MICROWAVE INTERFEROMETER FOR THE MEASUREMENT OF ELECTRON DENSITIES

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A MICROWAVE INTERFEROMETER FOR THE MEASUREMENT OF ELECTRON DENSITIES

by

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[redacted]

Submitted in partial fulfillment
for the degree of
MASTER OF SCIENCE IN PHYSICS
from the
UNITED STATES NAVAL POSTGRADUATE SCHOOL
May 1966

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ABSTRACT

The design, installation and operation of a microwave interferometer are described for the measurement of average electron densities on a steady state argon plasma confined in various magnetic field configurations. R band microwave components are utilized in making measurements of the phase shift of the "ordinary" electromagnetic wave when propagated through the plasma at 34, 35 and 36 GHz. An axial magnetic field from 540 to 8,370 gauss was used as the main field with a mirror magnetic field variable up to 10,300 gauss. The interferometer initiates the use of microwave measurements on the United States Naval Postgraduate School plasma facility.

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TABLE OF SYMBOLS

$\bar{n}$ - average electron density of plasma

f - frequency

$\Delta\phi$ - phase shift of transmitted signal

L - effective width of plasma beam

kT - electron temperature in electron volts

m - electron mass

c - velocity of light in free space

$\mathbb{D}$ - magnetic flux

q - charge on electron

$\bar{U}$ - average magnetic dipole moment

R_m - magnetic mirror ratio

B_o - magnetic field strength

1. Introduction.

Since its construction in 1963 the steady state plasma facility in the Plasma Research Laboratory at the United States Naval Postgraduate School has been studied by utilizing Langmuir probe and/or optical methods of diagnostics. The present project has been to design, install and make electron density measurements on this plasma with a microwave probing system operating in the 35 GHz range. The microwave free space method has been widely used in the measurement of parameters in the field of plasma physics and controlled thermonuclear fusion research[1,2,3,4]. A microwave interferometer similar to that used by Shiobara[5] was selected as the means of measuring the electron density in preference to a reflection apparatus which could only measure one critical density unless a r-f probe were actually inserted into the plasma beam with attendant difficulties. The interferometer also utilized more microwave equipment adaptable to future experiments at the facility. A microwave lens-horn system was designed to provide the directivity in the transmitted beam which is essential to reliable measurements. A hollow cathode arc discharge produced a plasma column which was then confined in an axial magnetic field variable up to 8,370 gauss. In order to simplify the calculations the system was designed to employ only the "ordinary" wave propagating perpendicular to the magnetic field.

2. Theory

Following World War II the much improved microwave technology permitted the use of free space transmission of electromagnetic waves through high density plasmas. Faraday rotation measurements performed at Berkeley in 1952 by R.F. Post et al. started the development of microwave diagnostics which are being used in Project Sherwood and other research. Recent work in measuring electron densities using the free space technique has been accomplished by Gardner [6], Shiobara [5], Buser and Buser [7], and McLane et al. [8].

The microwave interferometer is basically a circuit in which a signal from an auxiliary transmission path with adjustable amplitude and phase elements is compared against the primary transmitted signal to give a null in the absence of a plasma. When the plasma is introduced the output signal is a measure of the phase shift produced by the plasma which in turn is a function of the electron density only. With a calibrated phase shift device there is a continuous measurement of the density limited only by serious amplitude effects and detector sensitivity. The interferometer is especially useful in studying transient plasmas although not used for this purpose in the present case. After the interferometer is nulled it will produce a maximum signal when the plasma has shifted the phase of the transmitted wave by 180° and will return to a null at 360°, repeating as the angle

proceeds through multiple values of 180°, each cycle being commonly called a "fringe". A square law detector will yield a sinusoidal variation as the plasma density changes. With a steady state plasma the interferometer can be returned to a null manually.

Assuming that the plasma can be approximated by an adiabatic slab, a reasonable assumption since at the maximum magnetic field strength the plasma diameter is at least four times the transmitted beam width (see section 3.), the average electron density can be estimated after the method of Heald and Wharton[9] provided corrections for a strong magnetic field and finite plasma temperature are taken into account. Using the "ordinary" wave to eliminate the magnetic field effects on the propagated wave the average electron density can be shown to be:

$$\bar{n} = \frac{118.4\ f(\mathrm{Hz})\,\Delta\phi(\mathrm{rad})}{L(\mathrm{cm})\left[1+\left(\frac{kT}{mc^2}\right)^{\frac{1}{2}}\right]} \qquad 2\text{-}1$$

The critical density for a given frequency can also be observed by measuring the transmitted signal alone and provides a means of plotting peak density as a function of the magnetic field.

3. Experimental Apparatus.

The microwave system was designed to operate in the 30-36 GHz range with RG-96/U waveguide whose band center wavelength is 8.6 mm. For economic reasons much of the equipment was either obtained from other Naval Research

facilities or fabricated locally.

The basic circuit as seen in Fig. 1. consists of a signal source with output attenuator, travelling waveguide slotted line, frequency meter, 3 db directional coupler, a direct transmission path of waveguide sections and a lens-horn launching and receiving system, and an auxiliary transmission path with a calibrated attenuator and phase shifter. The two paths are joined at an interference comparator and connected to a crystal detector. The output signal detector is coupled to either a SWR meter operating as a null detector or to a video preamplifier and oscilloscope for visual display.

The signal source was a Hewlett-Packard 628A Signal Generator in tandem with a Hewlett-Packard 940A Frequency Doubler Set (see Fig. 2.) together producing one mw of output power over the full frequency range of 30-36 GHz. This combination has the particular advantage of direct reading frequency control and internal square wave amplitude modulation variable from 40 to 4,000 Hz.

The travelling waveguide slotted line was a DeMornay and Bonardi Model D-821 (see Fig. 2.) and was used primarily to align the system components. The frequency meter was a FXR Model U410A cavity type meter with a frequency range of 26.5-40.0 GHz and produced a one db dip in a SWR meter connected to the travelling detector. The output power was divided between the direct and auxiliary paths with a Hewlett-Packard R752A Directional

Coupler.

The most important part of the direct transmission path was the lens-horn launching and receiving system as illustrated in Fig. 3. The horns were identical and of the long rectangular pyramidal type with aperature dimensions of length 25 mm, width 12.5 mm and height 77 mm. Their theoretical gain was 35 db[1]. The lenses were two transparent center, Fresnel zone plates of a scaled design developed by Bitzer and Holt[11]. They have a focal length of 38.1 mm, an operating frequency of 37 GHz, a maximum diameter of 101.6 mm, six Fresnel zones of radius 18.05 mm, 26.17 mm, 32.82 mm, 38.77 mm, 44.30 mm and 49.54 mm respectively, a bandwidth of 12.3 GHz, a theoretical gain of 27.7 db and a 3 db beamwidth of $2^{o}21'$. They were constructed by cementing strips of pure aluminum foil in concentric rings onto a quartz window normally used in the viewing ports. The inside of the vacuum system was coated with a microwave absorbant consisting of 75% (by weight) Sauereisen No. 1 paste, 15% silicone carbide powder, 10% lampblack and enough thinner to make a smooth paste. The mixture was baked out after application to a pyrex section for 24 hours at $150^{o}F$ and for three hours at $400^{o}F$. This coating can withstand moderate plasma bombardment and reduces the reflection coefficient by approximately 10 db at 8 mm wavelength.

1. Heald and Wharton, Plasma Diagnostics With Microwaves (N.Y.: Wiley, 1965) p.327

In the auxiliary path the calibrated attenuator was a Hewlett-Packard R382A Precision Variable Attenuator with a range of 0-50 db. The phase shifter was locally fabricated from RG-96/U waveguide with a longitudinal slot 90 mm long cut through the top and bottom along the center line (see Fig. 4.). Since the cutoff frequency of this waveguide shifter is decreased by operation no higher undesired modes which would introduce significant phase errors are propagated. A captive screw is soldered to one wall and a manipulator attached which can spread apart or squeeze together the slit and produce an effectively longer electrical line. Phase shifts of two to four π are easily obtained which were more than adequate for the present project.

The interference comparator was an Ultramicrowave Hybrid Junction commonly called a "magic tee", which is a combination of an E-plane tee and an H-plane tee. Since the waveguide dimensions are such that only TE_{10} mode propagation is possible, and the E field in the parallel arm P is normal to that in the series arm S, there is no direct transmission between the series and parallel arms if they are symmetrically placed (see Fig. 5.). When waves of equal amplitude and phase enter the P and S arms the E fields cancel in side arm 2 and add in side arm 1. In the interferometer, arm P is fed from the direct transmission path and arm S is fed from the auxiliary transmission path, so that when the paths are adjusted

in both amplitude and phase no signal is seen in arm 2 and a signal of twice the amplitude is seen in arm 1. Arm 2 was terminated with a Sylvania IN26 Crystal Detector mounted in a FXR U212F Crystal Mount and was separated from the system by a .002 inch insulating film of plastic utilizing nylon screws to maintain a r-f path. This prevented any stray ground loop interference by the large currents associated with the magnetic field of the plasma facility. Arm 1 was terminated with a Microwave Associates 540AS Low Power Termination which absorbed the doubled signal. The null detector was a Hewlett-Packard Model 415A SWR Meter with a 75,000 ohm input impedance. The nonavailability of matched hybrid junctions precluded the use of a more desirable balanced bridge interferometer which has the advantage of greater sensitivity and has been used successfully with electronic phase shifters to follow rapid fluctuations in electron densities.

The plasma column was a nine foot long assembly of four inch diameter pyrex sections with access ports at 14 inch intervals (see Fig. 6.). The plasma source was a gas cathode type arc discharge operating in a reflex configuration using argon at a cathode pressure of approximately one micron. The longitudinal magnetic field was varied from 540 to 8,370 gauss.

4. Density Measurements.

To obtain the phase shift measurements the coated six arm pyrex section with Fresnel zone plate windows was

installed in the vacuum system at the port nearest the discharge region. The lens-horn system was fastened directly to the flanges and the remaining microwave apparatus positioned as far as practicable from the magnetic coils (see Fig. 7.) After preliminary alignment of the microwave components to insure maximum power transfer the magnetic field was turned on and the interferometer nulled. The phase shifter was then calibrated at different operating frequencies. The argon plasma was introduced at magnetic fields from 540 to 8,370 gauss at 100 amperes and a pressure of 3×10^{-4} mm Hg and the phase shift measured. The resulting average electron densities as a function of field strength are plotted in Fig. 8. At low magnetic fields the effective plasma width was estimated visually at six cm; at medium fields at four cm; and at high fields at 2.5 cm. These values were used to maintain the adiabatic approximation. In addition, the electron temperatures of the plasma as reported by Gall and Oleson [11] permitted the elimination of the temperature term in equation 2-1. The average electron density appears to increase linearly with the magnetic field except for some instability in the vicinity of 7,000 gauss. In this region, measurements of ion densities by McDaniel [15], which include points only into 5 mm from the axis of the column, show an increase in ion density. This indicates possible space charge effects with the electrons more concentrated in the center of the column which would

result in a lower average electron density if the effective width of the column were estimated from the larger visual width. At this magnetic field strength the predicted effective width of the plasma column would be approximately 2.1 cm compared to the visual width of 2.9 cm. The linear relationship can be explained in terms of the behavior of the gryo radius as the field is varied. In a uniform slowly time varying magnetic field the magnetic dipole moment is a constant, and as the magnetic field increases the particle energy increases at the same rate. The flux through the orbit of the particle is:

$$\Phi = \frac{2\pi m}{q^2}\bar{U} \qquad (4\text{-}1)$$

and must remain constant with time requiring the orbit to shrink with increased magnetic field so that the new gyro radius is inversely proportional to the square root of the magnetic field ratio. Since the electron density per unit length is inversely proportional to the cross sectional area of the beam and thus to the square of the gyro radius the density change should be directly proportional to the change in the magnetic field. Since the plasma facility has a mirror magnet which can be run from a separate power supply the effect of this magnet on the electron density was investigated. With the main magnetic field at 1,890 gauss the mirror field was varied from zero to 10,300 gauss. The mirror ratio at these fields ranged from one to about five. The results are plotted

in Fig. 9 and show that the electron density increases linearly with the mirror field. The mirror ratio of five produced only a 38% increase in the electron density indicating that a considerable number of electrons over the expected number are going into the escape cone (in velocity space). This may result from a large component of axial velocity near the center. Probe measurements seem to indicate a Maxwellian distribution of velocities, a disagreement with the above, although they were no taken nearer than 5 mm to the axis of the column. The theoretical electron densities as predicted by Glasstone and Lovberg 16 are also plotted in Fig. 9. Only a 38% actual increase is observed compared to a predicted value of 89%. Although a few electrons are lost at the discharge end of the column most are retained by the potential field there so the additional losses probably come from collisions in the plasma. All other parameters were held constant as the mirror field was varied.

5. Discussion

The measured electron densities are reliable to within 10%; the major discrepancy resulting from the rather crude method of operating the phase shifter which had an accuracy between 15-20 degrees. To measure the densities to less than 1% and to follow the fluctuations as the plasma grows and decays it is recommended that the present system be modified to include an electronic phase shifter or a precision machined calibrated manipulator.

Further improvement can be gained by using a well shielded video preamplifier, with well regulated power supply and d-c heater supply, mounted directly onto the crystal detector to provide minimum capacitive shunting and lessen the likelihood of stray pickup. Such a circuit is described by Heald and Wharton [9] and gives an amplification of 400 between zero and five MHz for input signals as low as one microvolt. This wide band amplifier together with a sawtooth generator and clipper circuit would allow a "zebra stripe fringe shift" presentation as developed by Gardner and Wharton [12] . Additional experiments which could be performed with this modified apparatus include density profiles similar to that done by Motley and Heald [13] and density fluctuations as described by von Gierke et al. [14] . With six arm pyrex sections simultaneous microwave and Langmuir probe experiments are also possible.

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MICROWAVE INTERFEROMETER

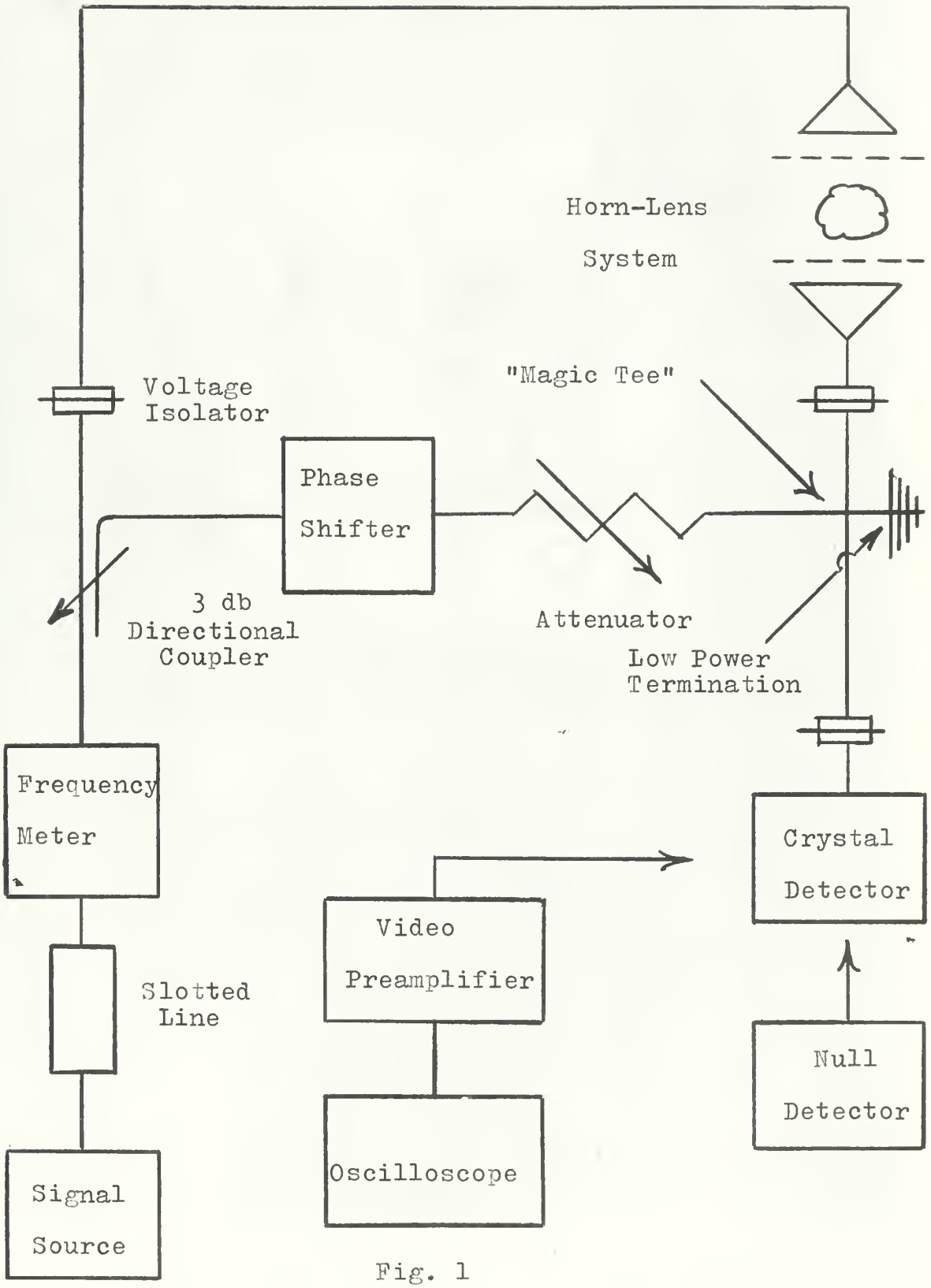
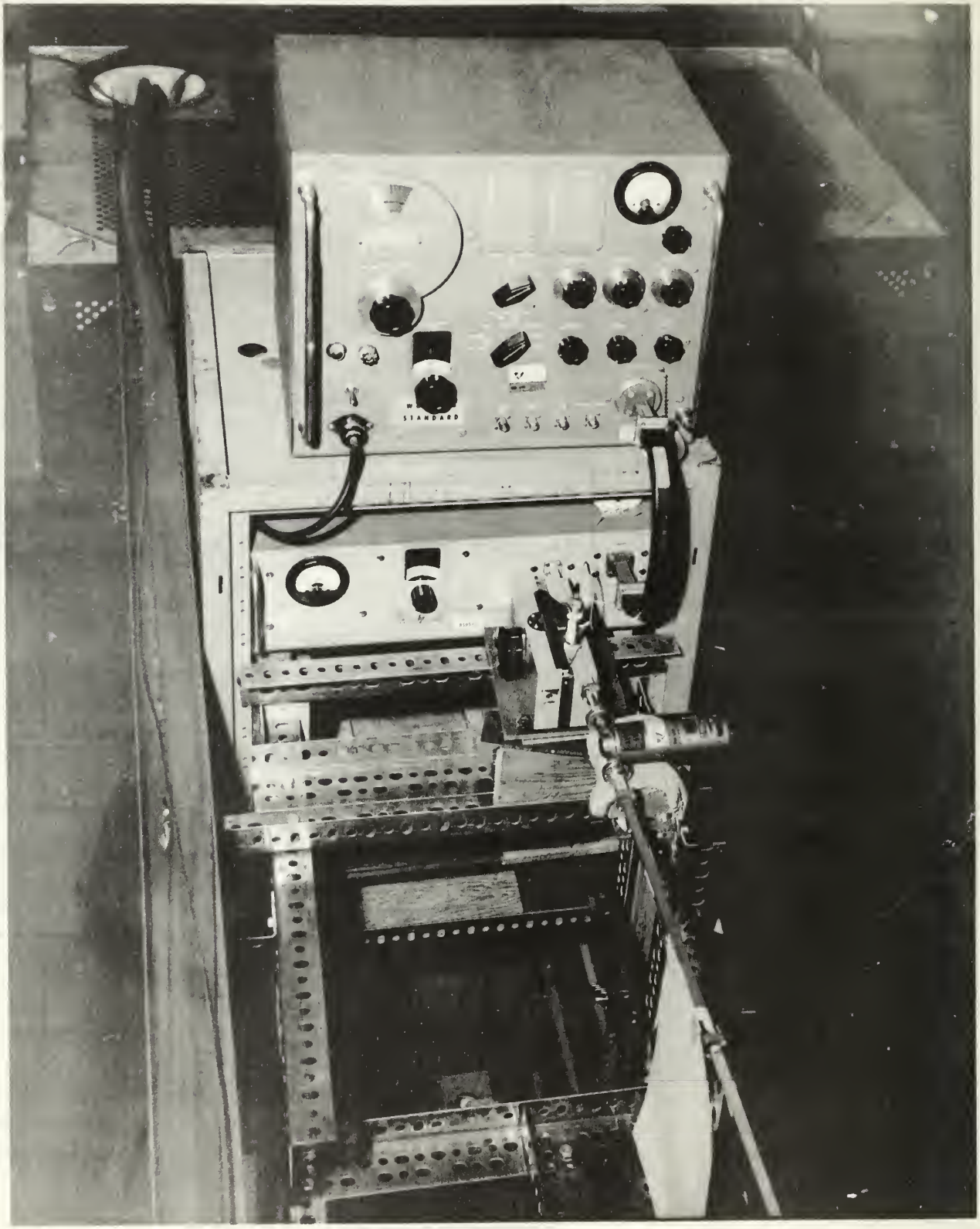


Fig. 1



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LENS-HORN SYSTEM

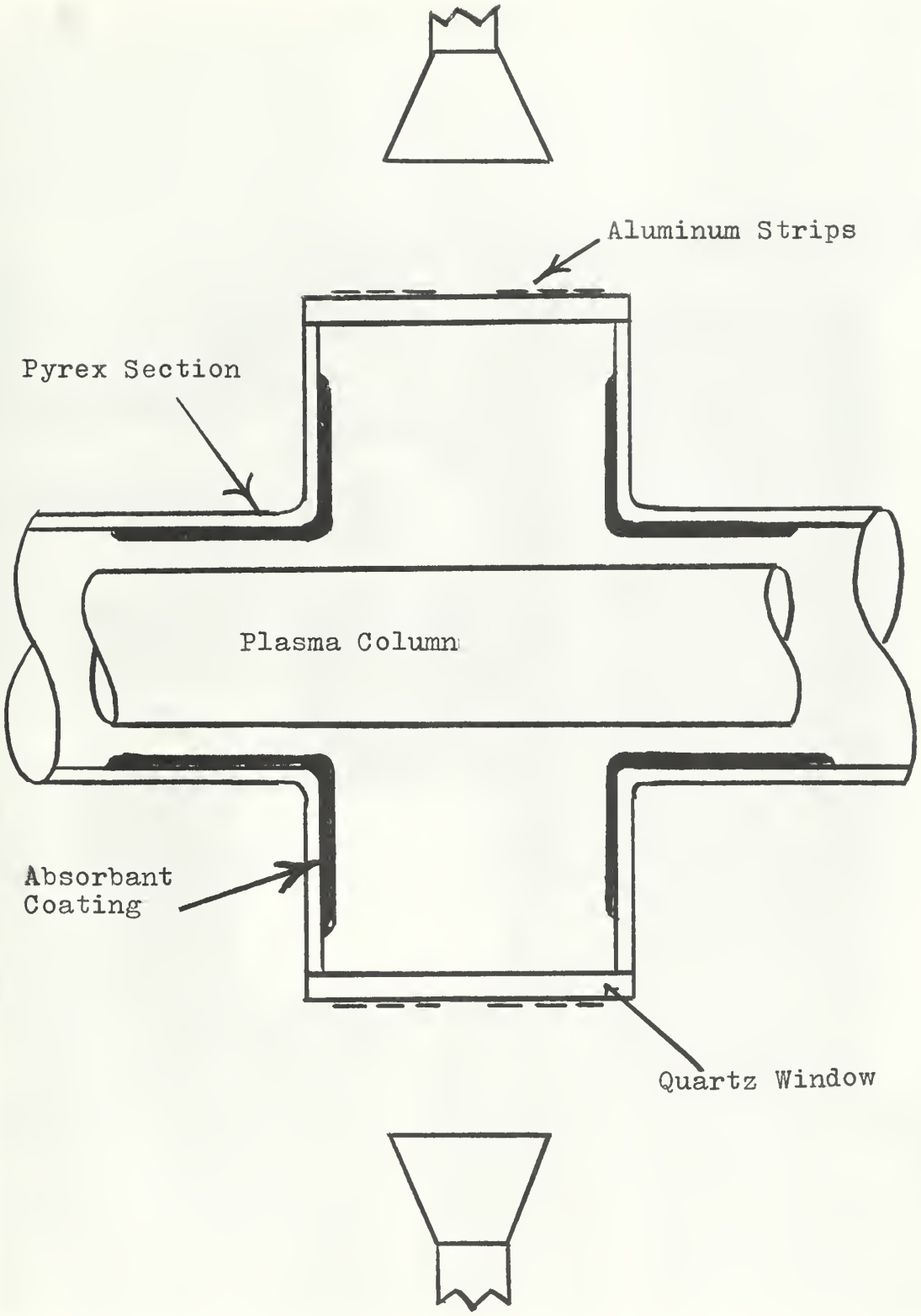
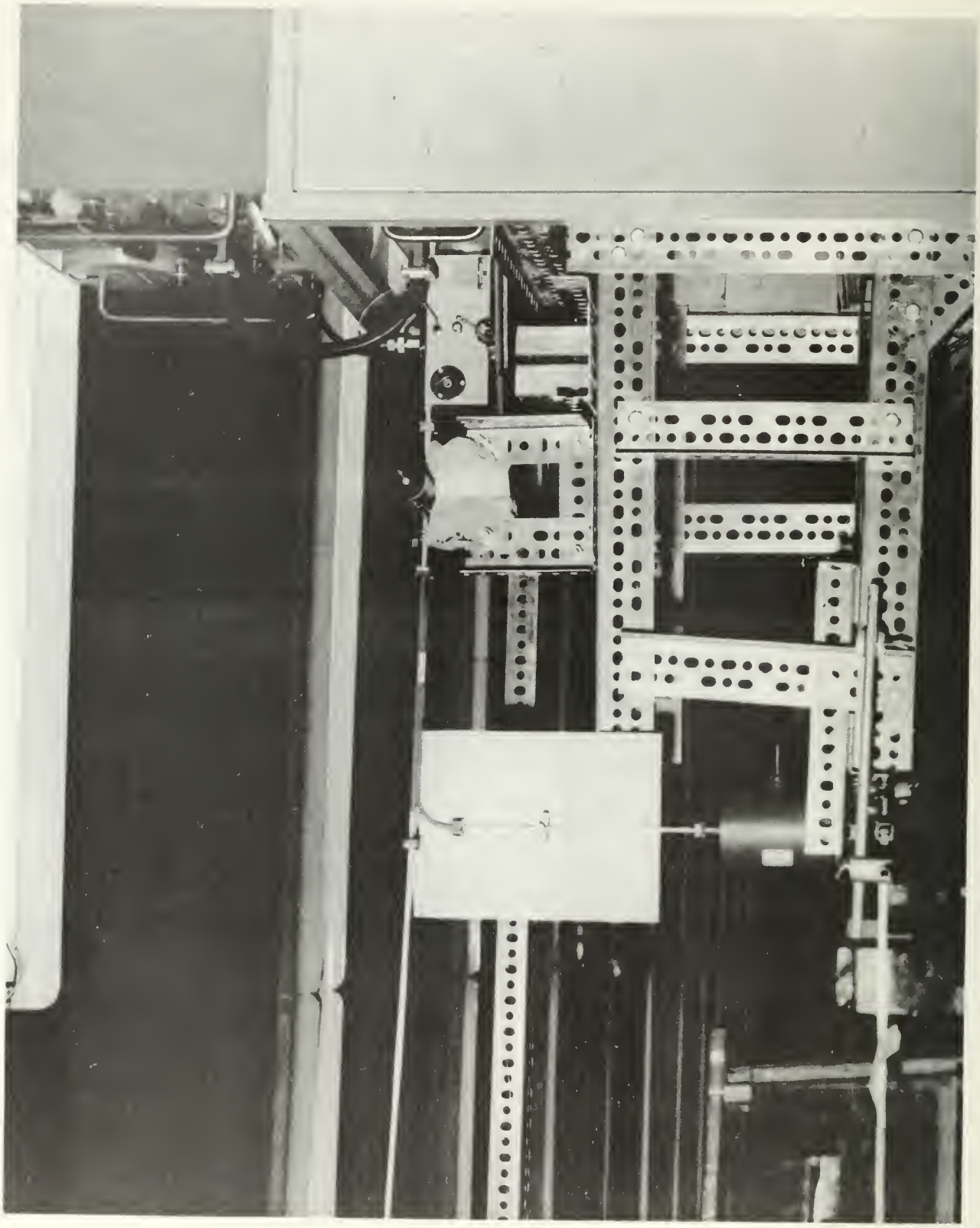


Fig. 3



HYBRID JUNCTION

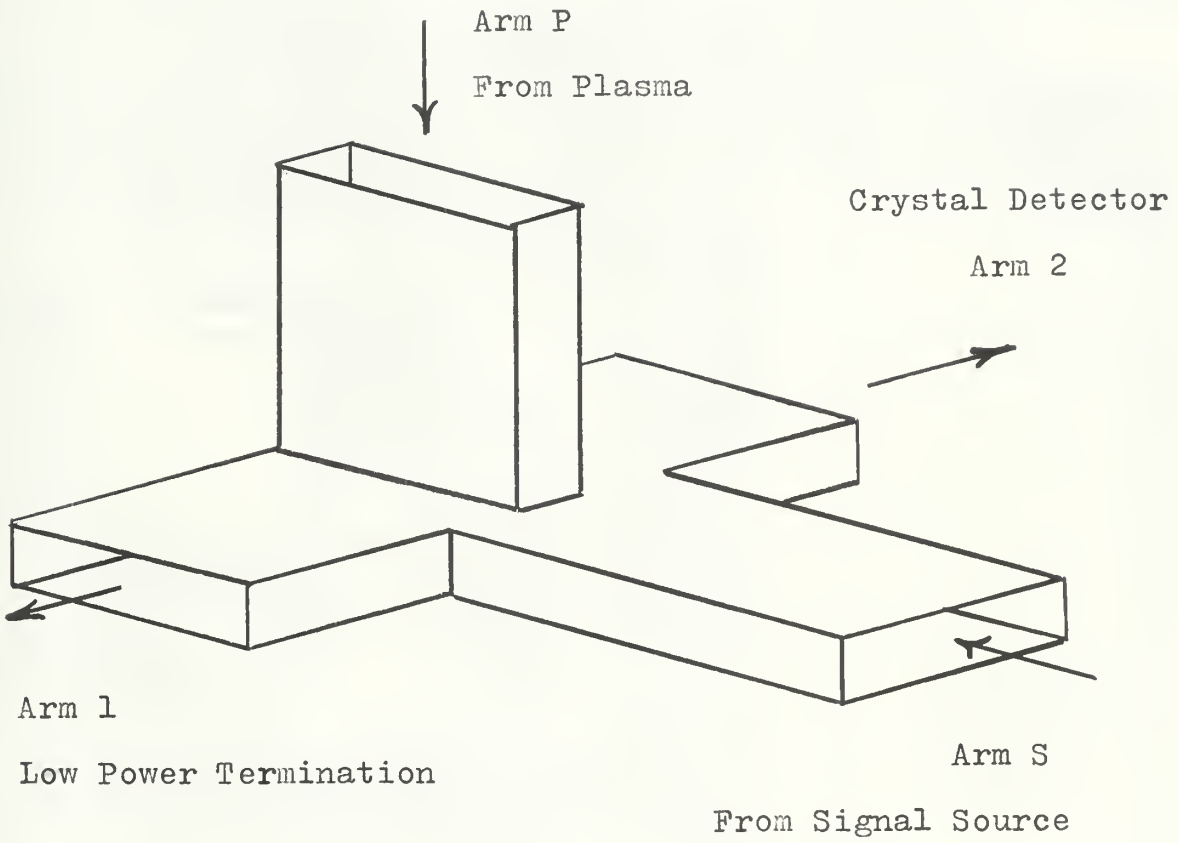


Fig. 5

DIAGRAM OF PLASMA DEVICE

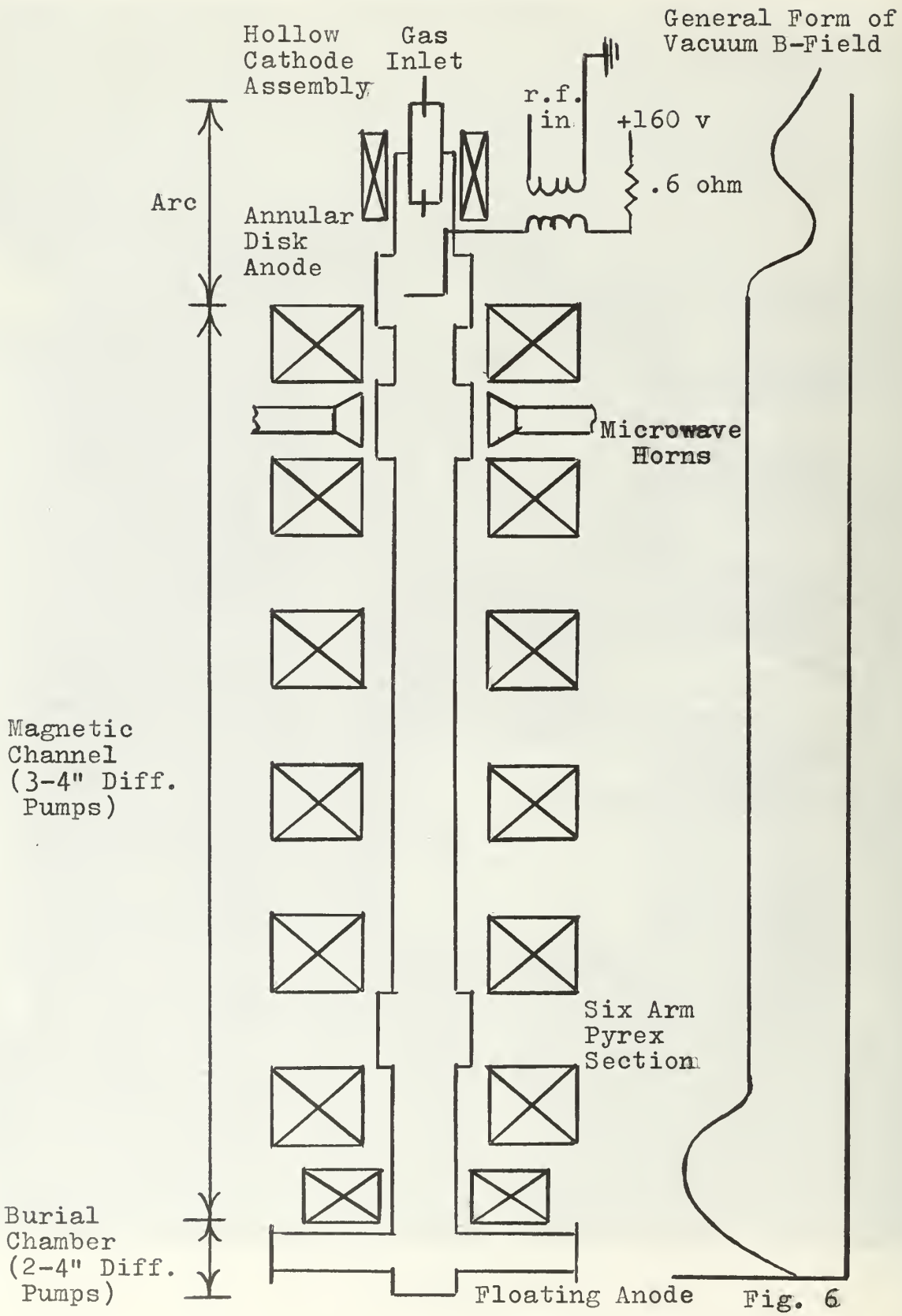


Fig. 6

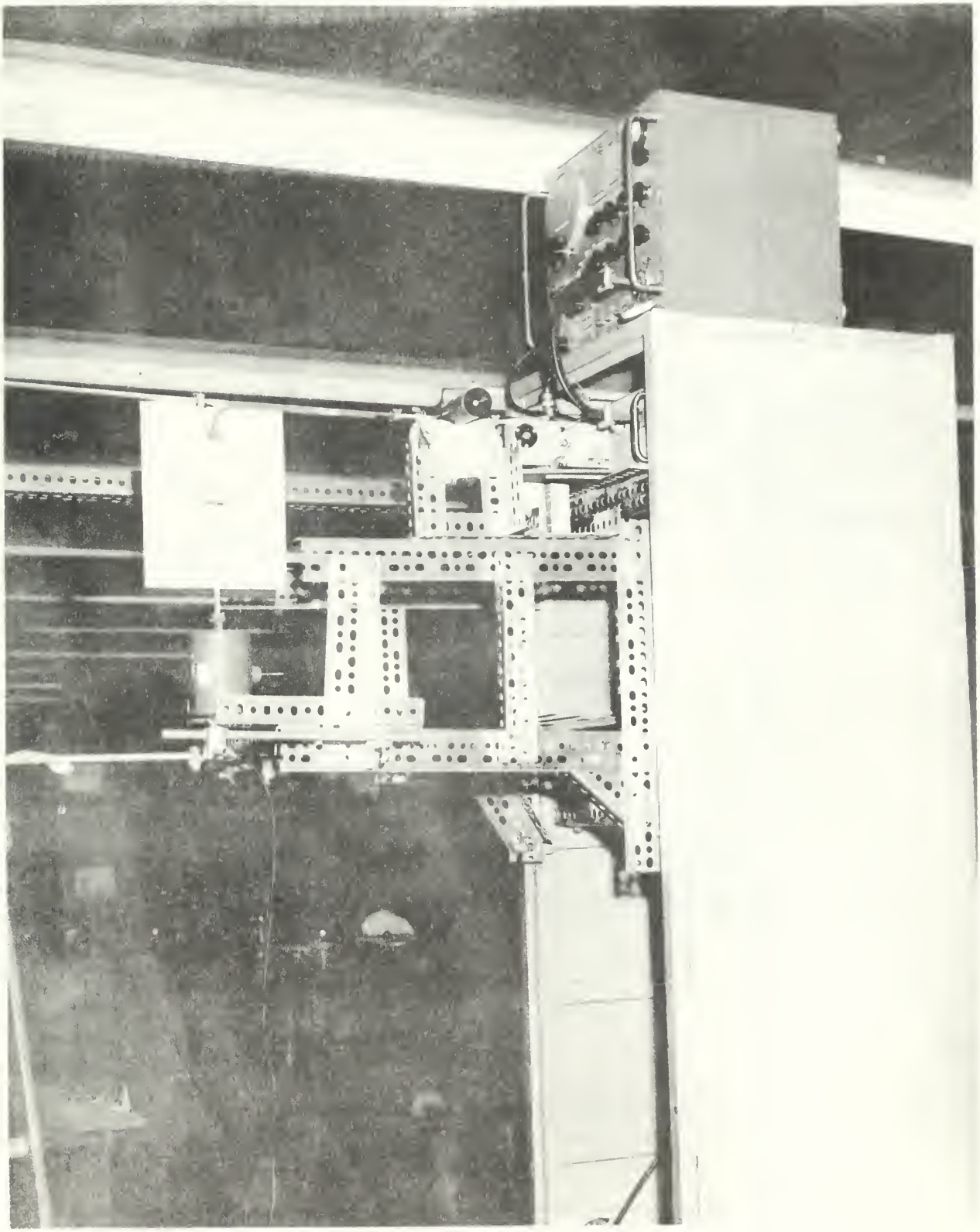


Fig. 8

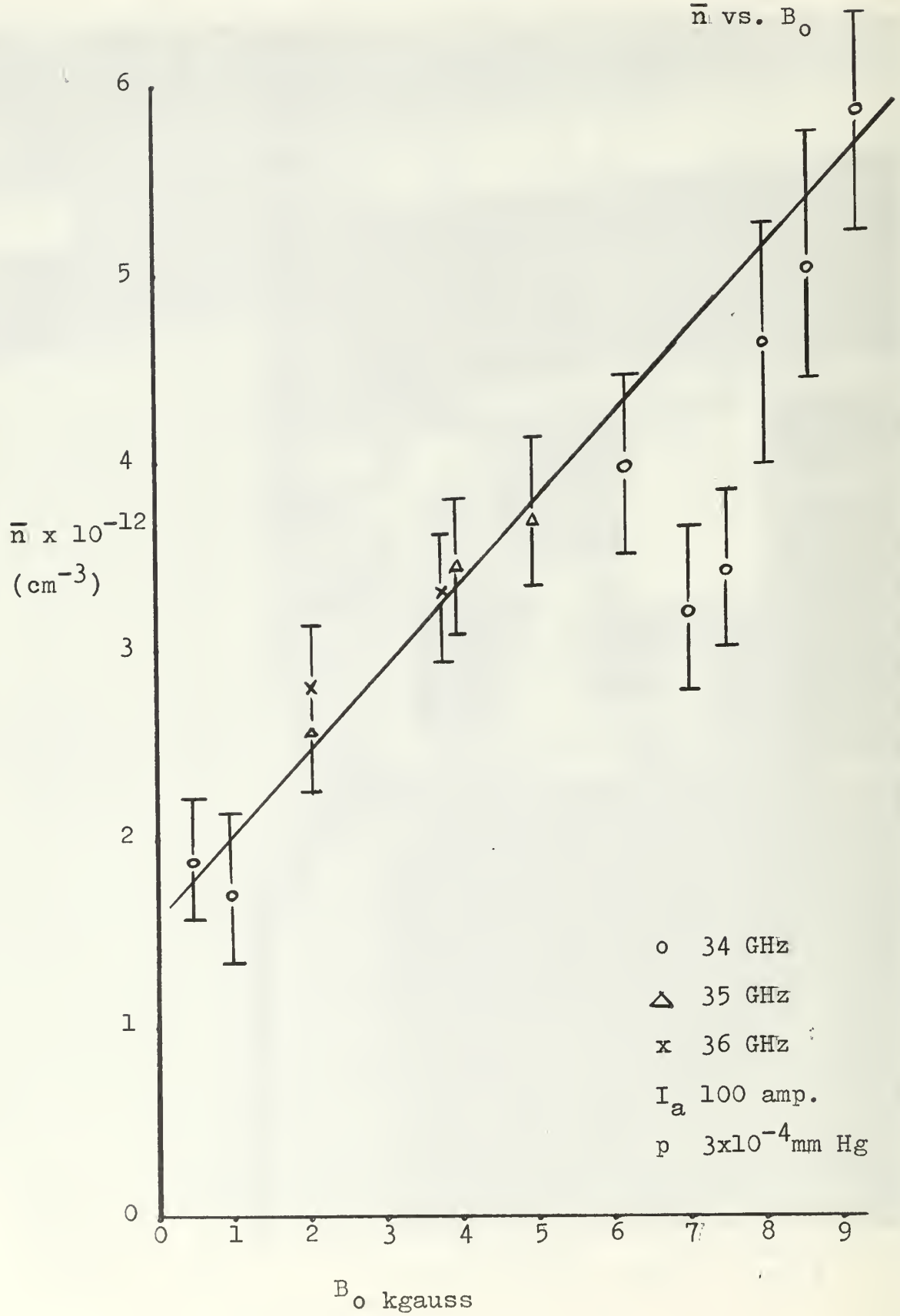
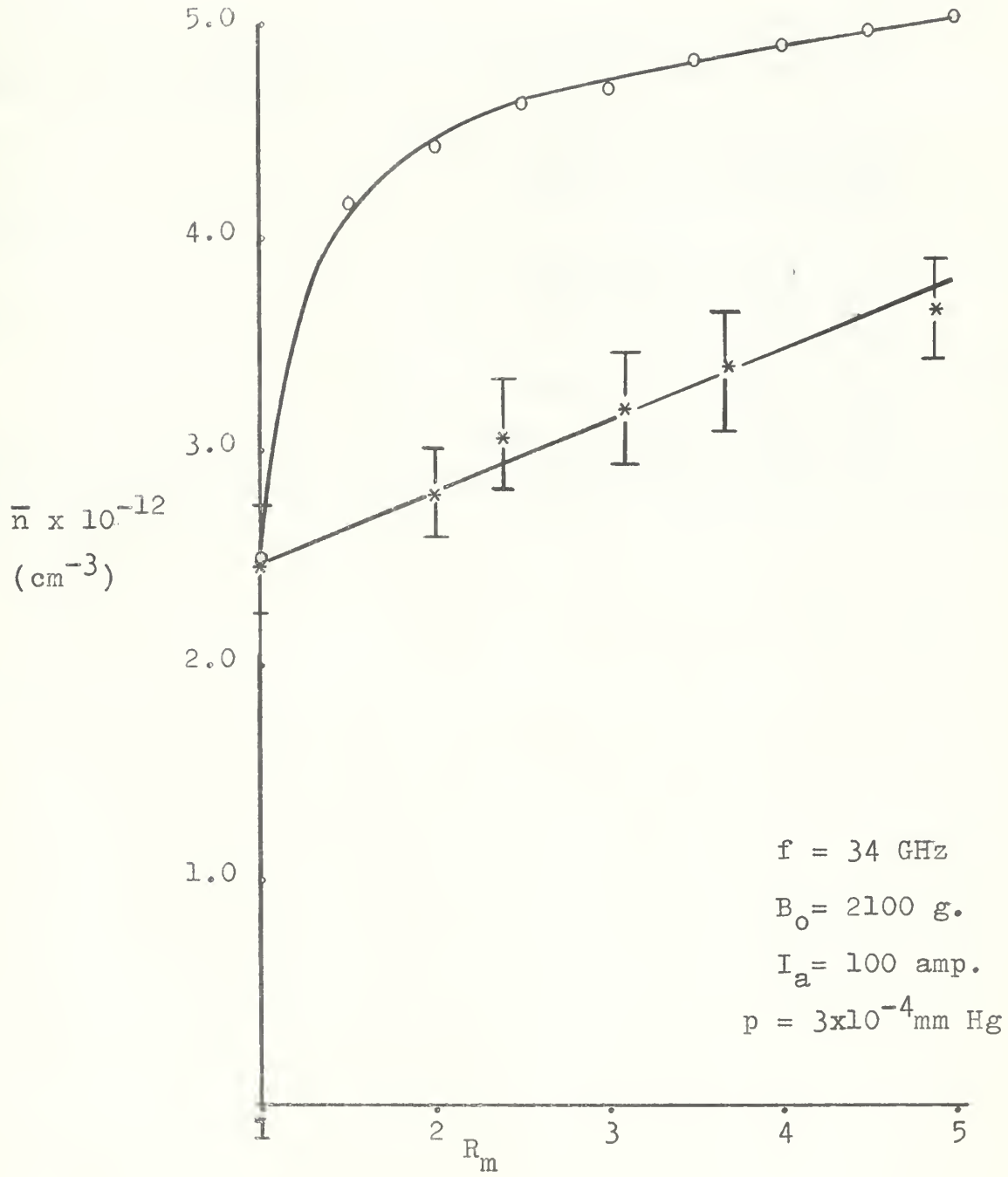

$\bar{n}$ vs. B_o
$\bar{n}$ x 10^{-12}
(cm^{-3})
0
1
2
3
4
5
6
0
1
2
3
4
5
6
7
8
9
B_o kgauss
o 34 GHz
△ 35 GHz
x 36 GHz
I_a 100 amp.
p $3x10^{-4}$mm Hg

Fig. 9

$\bar{n}$ vs. R_m

o theoretical

* actual



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1. ORIGINATING ACTIVITY *(Corporate author)*

U.S. Naval Postgraduate School
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2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE

A MICROWAVE INTERFEROMETER FOR THE MEASUREMENT OF ELECTRON DENSITIES

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

USNPGS Thesis 2 August 1965--24 May 1966

5. AUTHOR(S) *(Last name, first name, initial)*

Nelson, Raymond J.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
24 May 1966	29	16

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	
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10. AVAILABILITY/LIMITATION NOTICES

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
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fringe						
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phase shift						

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